PB90-245242

Foliar Leaching and Root Uptake of Ca, Mg and K in Relation to Acid Fog Effects on Douglas-Fir

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1990

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1. REPORT NO. EPA/600/J-90/069	2.
3. PB90-245242	
4. TITLE AND SUBTITLE Foliar leaching and root uptake of Ca, Mg and K in relation to acid fog effects on Douglas-fir	5. REPORT DATE
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) David P. Turner[1], and David T. Tingey[2]	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS [1]NSI, ERL-Corvallis; [2]US EPA, ERL-Corvallis, OR	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS US Environmental Protection Agency Environmental Research Laboratory 200 SW 35th Street Corvallis, OR 97333	13. TYPE OF REPORT AND PERIOD COVERED Journal Article
	14. SPONSORING AGENCY CODE EPA/600/2

15. SUPPLEMENTARY NOTES

1990. Water,Air and Soil Pollution 49:205-214.

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 12
	20. SECURITY CLASS (This page) Unclassified	22. PRICE A03

EPA Form 2220-1 (9-73)

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EPA/600/J-90/069

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FOLIAR LEACHING AND ROOT UPTAKE OF Ca, Mg AND K IN RELATION TO ACID FOG EFFECTS ON DOUGLAS-FIR

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(Received August 29, 1989; revised October 26, 1989)

Abstract. The impact of acid fog on foliar leaching and root uptake of Ca, Mg, and K by Douglas-fir (*Pseudotsuga menziesii*) seedlings was examined. In a factorial experiment, 1-year old seedlings were grown in solution culture at two levels of nutrient availability (low and moderate) and exposed twice a week (4 hr per event) for 12 weeks to fog at pH 5.6 or pH 3.1. Throughfall enrichment of Ca, Mg and K was determined from drip collectors at the base of each seedling and root uptake rates for trees under the moderate nutrient regime were evaluated by monitoring nutrient solution depletion. Throughfall enrichment was higher in the pH 3.1 fog than the pH 5.6 fog but much of the enrichment appeared to be wash off of precipitate from previous fogs. The amounts of nutrients coming off of the foliage with the low pH fog were small relative to the daily uptake rates. Foliar concentrations of K and Mg at the end of the exposures were lower under the low nutrient regime but were not affected by fog pH. Comparisons of wax weight and examinations of epicuticular wax by electron microscopy did not indicate a significant impact from exposure to the low pH fog.

1. Introduction

The observation that some forms of forest decline in central Europe are associated with the symptoms of foliar nutrient deficiencies has prompted the hypothesis that increased leaching of foliage by acidic rain or fog is a significant contributing factor to the decline (Rehfuess, 1983). Laboratory, chamber and field studies have revealed that foliar leaching rates of nutrient cations such as K, Mg and Ca are increased as H^+ concentration of the rain or mist solution increases (Tukey, 1970; Scherbatskoy and Klein, 1983; Waldman and Hoffman, 1988). However, assessment of the ecological significance of such losses is difficult. Two areas of uncertainty involve the capacity of the acidic precipitation to draw down nutrient reservoirs of the foliage in cases where the supply of nutrients to the roots is limited and the ability of trees to replace losses of nutrient cations by compensatory uptake in the roots when nutrients are readily available.

This study was designed to evaluate the interaction of foliar cation leaching and

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Water, Air, and Soil Pollution 49: 205–214, 1990.

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nutrient availability to the roots in the response of Douglas-fir (*Pseudotsuga menziesii*) seedlings to simulated acid fog. The experiment tested the hypothesis that under conditions of moderate nutrient availability, any foliar leaching associated with low pH fog can be compensated for by root uptake. Foliar nutrient concentrations should thus not decrease in response to multiple fog exposures. Response to low pH fogging in the case of low nutrient availability was also examined in order to determine if acid fog can draw down foliar nutrient levels when uptake is restricted.

2. Materials and Methods

Douglas-fir tree seedlings were grown in solution culture, in order to regulate nutrient availability, and monitor nutrient uptake rates. Seedlings were exposed to twice weekly fogs over a 12 week period. The split plot experimental design included 2 fog pH regimes (pH 5.6 and 3.1) and 2 nutrient level regimes (moderate and low). Rates of foliar leaching and root uptake of Ca, Mg and K on a per tree basis (see below) were determined periodically, and at the end of the experiment all seedlings were harvested for comparisons of dry weights and tissue nutrient concentrations. The experiment was run twice.

The exposures took place in fog chambers (2 per pH treatment) located in a glasshouse. Air circulating through the chambers was charcoal filtered. Fog events lasted 4 hr (deposition rate of 0.5 cm hr^{-1}) and occurred twice weekly for 12 weeks. The total fog exposure of 96 hr over an 84 day period was based on fog occurrence data from two sites representative of the Coastal West (Hogsett and Tingey 1989). Mean mass particle size of the fog droplets was 33 μm (Particle Measuring Systems CSASP-100-HV-SP optical particle counter).

The chemistry of the low pH fog solution was based on California Air Resources Board monitoring data for Henninger Flats, a heavily polluted site near Los Angeles (Waldman *et al.*, 1985). The nitrate (1490 μeq L^{-1}) to sulfate (800 μeq L^{-1}) ratio was 2:1 and the pH of 3.1 was close to the median pH of 2.9 for that site. The concentrations of ammonium (10.6 mg L^{-1}), Ca (3.0 mg L^{-1}), Mg (1.9 mg L^{-1}) and K (1.6 mg L^{-1}) were close to the medians for that site. The high pH fog solution was a 10 fold dilution of the pH 3.1 solution with a titration to pH 5.6 using NaOH.

The 1-year old seedlings (10 per treatment) were obtained from a commercial nursery (Crown Zellerbach, seed zone 452) and transplanted to solution culture for a 4 week equilibration period. Trees were grown in individual solution culture vessels (1 L) arranged in banks of five. Solution for each set of 5 trees was in continuous circulation with a 20-L reservoir which was renewed every two weeks. Care was taken to prevent contamination of nutrient solutions by fog solution. Elemental ratios in the nutrient solutions were those recommended for Douglas-fir by Ingestad (1979) with concentrations of N at 1 (low treatment) and 10 (moderate treatment) μg mL^{-1}. The nitrogen was 60% nitrate and 40% ammonium. The 10 μg mL^{-1} N nutrient regime was low relative to concentrations used by Ingestad

(1979) but it gave good growth under these experimental conditions whereas the trees in the low nutrient regime grew very little and looked chlorotic by the end of the experiment. Nutrient solution pH was maintained above pH 4.0 by additions of NaOH. Nutrient solutions were cooled to prevent high mid-day temperatures and mean daily nutrient solution temperature over the course of the experiment was 19.5 ± 1.6 °C.

The magnitude of throughfall enrichment was determined from volumes of foliar drip and differences in concentration between the drip and the fog solutions. Foliar drip was collected by polypropylene funnels fitted around the base of each tree seedling. Throughfall solution (approximately 50 mL per tree) accumulated in capped sample bottles fed by drainage lines connected to the base of the funnels. A control funnel was used to account for residue on the test collection funnels. Solution samples were analyzed for pH within 2 hr with a combination electrode and for Ca, Mg, and K using inductively coupled plasma analysis (McQuaker *et al.*, 1979). Throughfall was analyzed for fog events at weeks 4, 8, and 12.

Rates of cation uptake (net cation influx per tree per 24 hr) under the moderate nutrient regime were determined from changes in volume and in concentrations of Ca, Mg and K in the nutrient solutions over 2 week periods. Nutrients were depleted approximately 50% over that interval. Under the low nutrient regime, concentrations of all nutrients were reduced to detection limits within a few days and consequently uptake was not measured.

At the end of the experiment, trees were harvested and root and shoot dry weights were determined. Concentrations of Ca, Mg, and K in roots, stems, first year needles and second year needles were analyzed. All analyses for elemental concentrations of Ca, Mg and K were made on tissue digests using ICP (McQuaker *et al.* 1979).

For the first run of the experiment, selected needles (3 or more per treatment) were examined at the end of the exposures by scanning electron microscopy (SEM) for evidence of epicuticular wax erosion. Needles were air dried and coated with a 60/40 gold palladium alloy by vacuum evaporation before analysis by an Amray 1000A scanning electron microscope. Analyses were performed at the Oregon State University Electron Microscope Facility. Foliar samples from 3 trees per treatment were also extracted (60 s) with chloroform (1:10, w:v) for cuticular wax content.

Treatment effects of pH and of nutrient regime as well as comparisons within a pH or nutrient regime were made using analysis of variance. Comparisons were not made across nutrient regimes for throughfall enrichment because of a difference in the amount of foliage per tree. The results of the two runs of the experiment were similar, and results are reported for the second run.

3. Results

Dry weights of roots and shoots at the end of the 12 week experiment increased in response to higher levels of nutrient availability (Figure 1). Nutrient concentrations for K and Mg in first and second year needles also increased in response to higher

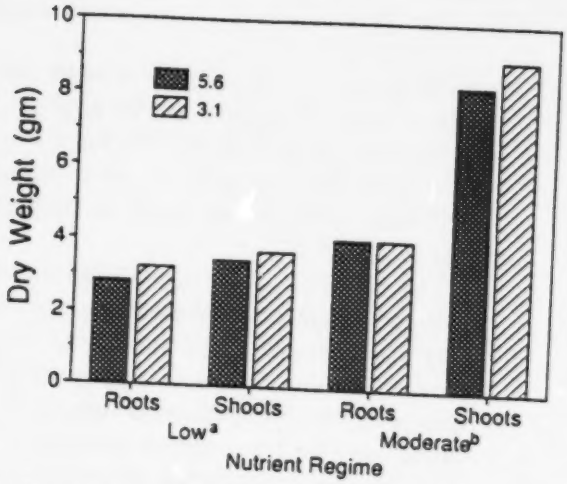

Fig. 1. Dry weight of roots and shoots after fog exposures. Differences between fog pHs within roots and shoots were not significant ($p > 0.05$). Letters adjacent to the nutrient regimes indicate the significance of an overall nutrient treatment effect.

levels of nutrient availability (Figure 2). Within a nutrient regime, low pH fogs did not significantly affect biomass production (Figure 1) and total nutrient content (Table I) and did not cause a significant decrease in nutrient concentration of the foliage (Figure 2).

Throughfall enrichment of Ca, Mg, and K was considerably higher in a pH 3.1 fog than in a pH 5.6 fog under both nutrient regimes (Table II). The amounts of these elements coming off the foliage increased over the course of the experiment, probably because of the increasing foliar biomass. The greatest absolute enrichment was of K. The ratio of K removed to Ca removed was greater under the moderate nutrient regime (Table II). This difference paralleled a similar difference in the K:Ca ratio in foliar concentrations (Figure 2), suggesting that K leaching reflects foliar K status. The pH did not differ significantly between throughfall of any of the treatments and the relevant control collectors.

Because there was no wind in the chambers, droplets that were left after fog events eventually evaporated, leaving a residue of mineral salts to be washed off by the next fog. Thus, the leaching *per se* (removal of nutrients from within the cuticle and apoplast) was less than the throughfall enrichment. The product of the droplet holding capacity (approximately 20 mL), estimated by shaking droplets off of comparably sized tree seedlings after a fog event, and the concentrations of the elements in the fog solution yielded quantities similar in magnitude to the observed throughfall enrichment for Ca and Mg. The droplet holding capacity was smaller than the volume of throughfall, indicating a several fold turnover during the course of a fog event. These observations provide evidence that much of the throughfall enrichment of Ca and Mg was probably solubilization and wash off of residue from previous fog events. The enrichment of K, however, was higher

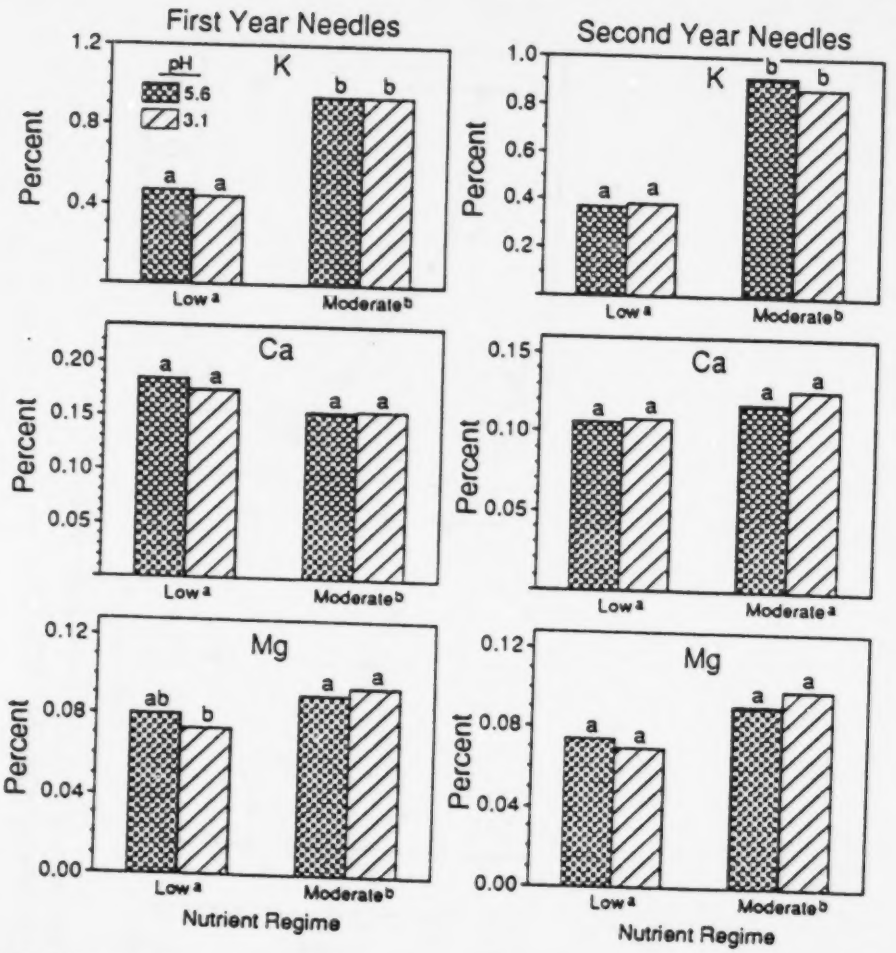

Fig. 2. Nutrient concentrations of 1st and 2nd year foliage after fog exposures. Within an element, the same letter across columns indicates no significant difference ($p > 0.05$). Letters adjacent to the nutrient regimes indicate the significance of an overall nutrient treatment effect.

than would be expected from the wash off of residue, suggesting a leaching effect.

For all three elements, uptake rates did not differ significantly between the two fog treatments and results were therefore pooled across fog pH treatments (Figure 3). Uptake rates (μg tree^{-1} 24 hr^{-1}) were greatest for K followed by Ca and Mg. For K and Mg, daily uptake rates under the moderate nutrient regime increased with time and for all three elements uptake rates were consistently greater than amounts coming off in the throughfall during a fog event (μg tree^{-1} 4 hr pH 3.1 fog event^{-1}).

There was no visual evidence of foliar injury due to pH 3.1 fog nor did SEM analyses indicate that epicuticular wax crystals were damaged or eroded. Total cuticular wax as a percent of dry weight was significantly greater under the moderate nutrient regime, but there was no effect of fog pH (Figure 4).

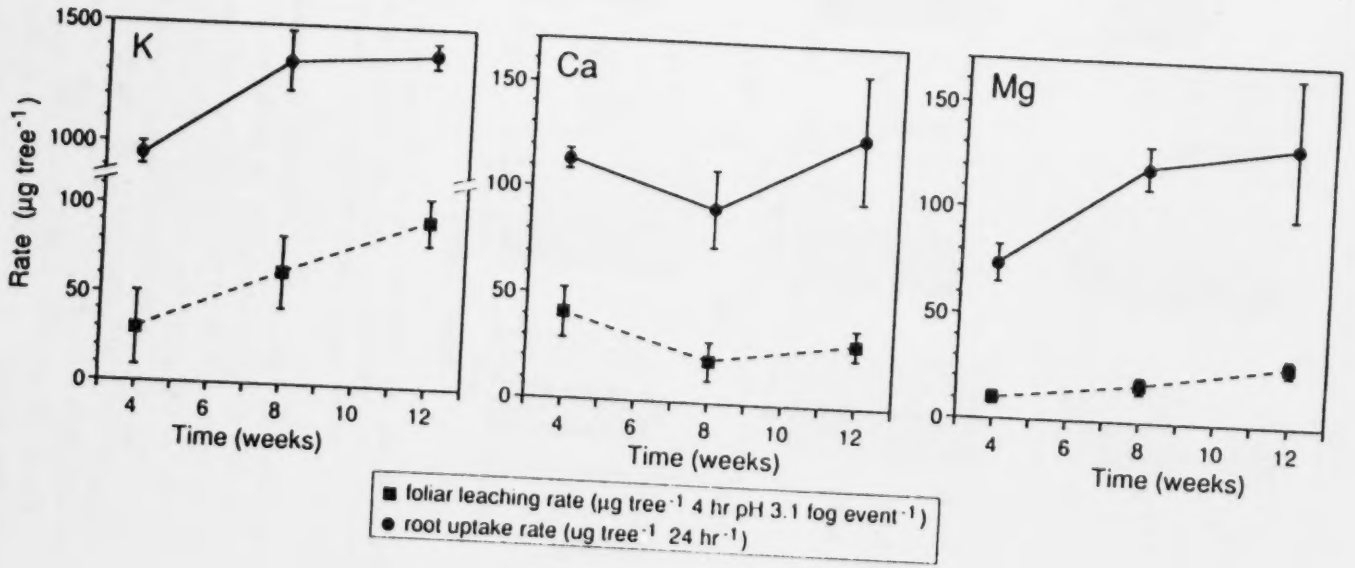

Fig. 3. Rates of root uptake and foliar leaching at weeks 4, 8, and 12 for trees under the moderate nutrient regime. Error bars are ± standard deviation. The measured leaching is an underestimate of total leaching at week 12 because of foliage extending over the edge of the throughfall collectors.

TABLE I

Total K, Ca, and Mg per tree seedling at the end of the experiment. Values are based on means (by treatment) of tissue dry weights and elemental concentrations

Nutrient regime	Fog pH	K	Ca	Mg
		mg tree^{-1}		
Moderate	5.6	103.40	12.87	9.47
Moderate	3.1	108.52	14.25	10.53
Low	5.6	26.33	7.38	3.20
Low	3.1	27.21	7.32	3.78

TABLE II

Throughfall enrichment of K, Ca, and Mg during one 4 hour fog event. Numbers in parenthesis are standard deviations. Different superscripts within an element and nutrient regime indicate significant differences ($p > 0.05$)

Nutrient regime	Fog pH	K	Ca	Mg
		μg tree^{-1} fog event^{-1}		
Moderate	5.6	19 (12)^a	9 (5)^a	2 (1)^a
Moderate	3.1	63 (20)^b	20 (9)^a	18 (4)^b
Low	5.6	1 (2)^a	3 (4)^a	1 (1)^a
Low	3.1	16 (3)^a	19 (6)^b	13 (4)^b

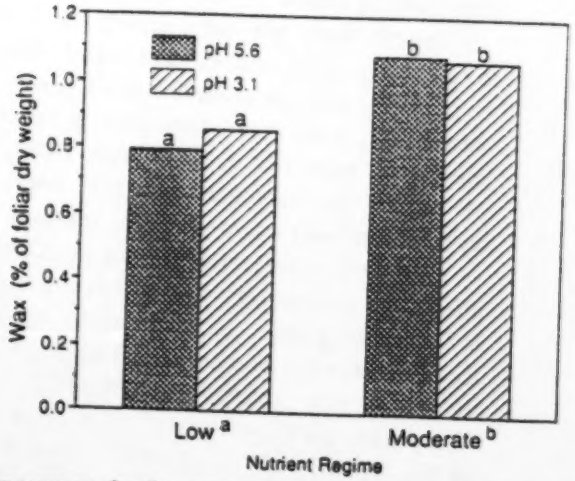

Fig. 4. Foliar wax contents after fog exposures. The same letter across columns indicates no significant difference ($p > 0.05$). Letters adjacent to the nutrient regimes indicate the significance of an overall nutrient treatment effect.

4. Discussion

The results suggest that foliar leaching was not a significant factor in the growth and mineral nutrition of Douglas-fir seedlings under these experimental conditions. The growth and foliar nutrient concentrations of the seedlings responded over the experimental time frame to the nutrient availability but not to the fog pH. With moderate nutrient availability, the leaching losses were readily compensated for by nutrient uptake. The differences between rates of leaching and uptake were large enough that compensatory uptake was not detectable. With low nutrient availability, the amount of the nutrient losses due to leaching was too small to make a difference in foliar nutrient pools. Biomass production of soil grown Douglas-fir seedlings in other exposures to acidic fog (Turner *et al.*, 1989) and acidic mist (McColl and Johnson, 1983; McColl and Firestone, 1987) has generally not been detrimentally affected when precipitation pHs have ranged from 3.0 to 5.6. Foliar nutrient concentrations of conifer seedlings exposed to acidic precipitation (MacDonald *et al.*, 1986; Abouguendia and Baschak, 1987) have likewise generally not been affected.

In the limited leaching that did occur, the greater effect on K relative to Ca and Mg may relate to it being a monovalent ion. As such it would diffuse more readily through the cuticle (McFarlane and Berry, 1974) and be less tightly bound than divalent Ca and Mg to the cation exchange sites in the cuticle (Schonherr and Huber, 1977) and cell walls (Crooke *et al.*, 1964). A greater rate of K leaching in the low pH fog is expected because H+ ions in the fog solution would readily drive K+ off these exchange sites. Field studies of throughfall (Cronan and Reiners, 1983; Lovett *et al.*, 1985) and laboratory studies of foliar leachate (Skiba *et al.*, 1986) have indicated the importance of cation exchange in the foliar leaching process.

Although there was not a strong effect of the low pH fog on epicuticular wax in this study, other studies have found effects on foliage of some conifers (Rinallo *et al.*, 1986) and herbaceous species (Percy and Baker, 1987). Solutions acidified with H_2SO_4 were more damaging to epicuticular wax of Norway spruce (*Picea abies*) than solutions acidified with HNO_3 (Rinallo *et al.*, 1986). Effects of low pH fog on wax may thus have been limited in this study in part because nitrate was the dominant anion in the fog solution.

In the field, a variety of factors would influence how acidic fog or precipitation affects the mineral nutrition of trees. Besides the effects of pH, the magnitude of foliar leaching could be modified by the chronic nature of exposure to fog and cloud water in some ecosystems (Vogelman *et al.*, 1968), possible accelerated leaching associated with exposures to elevated O_3 (Bosch *et al.*, 1986) and organic anions (Grossman, 1988), accelerated leaching associated with aging of the foliage (Tukey, 1978), and the marginal cuticular development of some high altitude tree species (DeLucia and Berlyn, 1984). Limitatioins on uptake rates, such as those associated with soil acidification, could also contribute to nutrient stress.

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5. Conclusion

Exposure to pH 3.1 fog did not appear to injure or reduce growth of Douglas-fir seedlings under conditions of either low or moderate nutrient availability. The low pH fogs increased foliar leaching to a limited extent, but the magnitude of leaching was small relative to potential rates of nutrient uptake.

Acknowledgments

We thank J. W. Munger (California Institute of Technology, Pasadena) for determination of fog particle size and A. Soeldner (Oregon State University) for the electron microscopy work. The research was supported by funds provided by the Western Conifers Research Cooperative, within the joint US Environmental Protection Agency-USDA Forest Service Forest Response Program. Parts of this research were presented at the 14th Int. Meeting for Specialists in Air Pollution Effects on Forest Ecosystems, IUFRO, Interlaken, Switserland (October 2–8, 1988).

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